THE LOS ALAMOS/ARZAMAS-16 COLLABORATION ON ULTRAHIGH MAGNETIC FIELDS AND ULTRAHIGH ENERGY PULSED POWER

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Introduction

The end of the Cold War has made possible some remarkable scientific adventures--joint research projects between scientific institutions of the United States and the Russian Federation. Perhaps most unprecedented of the new partnerships is a formal collaboration which has been established between the All-Russian Scientific Research Institute of Experimental Physics (VNIIEF) and the Los Alamos National Laboratory (LANL), the two institutes which designed the first nuclear weapons for their respective countries.

In early 1992, emerging governmental policy in the US and Russia began to encourage "lab-to-lab" interactions between the nuclear weapons design laboratories of the two countries. Each government recognized that as nuclear weapons stockpiles and design activities were being reduced, highly qualified scientists were becoming available to use their considerable skills in fundamental scientific research of interest to both nations. VNIIEF and LANL quickly recognized a common interest in the technology and applications of magnetic flux compression, the technique for converting the chemical energy released by high-explosives into intense electrical pulses and intensely concentrated magnetic energy.

The principles of magnetic flux compression, pioneered at VNIIEF by a team originally lead by Nobel Peace Laureate Andre D. Sakharov and at Los Alamos by a team lead by C. M. Fowler, are well known. If a region containing magnetic flux is surrounded by a perfect conductor, the magnetic field strength and magnetic energy can be increased by decreasing the cross-sectional area of the region. This is illustrated in Fig. 1a, where the initial cross-sectional area A_o having an initial magnetic field B_o is reduced to A_F. Faraday's Law requires that magnetic flux is conserved, i.e.,

$$B_F A_F = B_o A_o$$

where, B_F is the final magnetic field strength. Therefore, the final magnetic field strength is

$$B_F = B_o \,(A_o/A_F)$$

and the final magnetic energy per unit length is

$$(1/2)\,(B_F)^2\,A_F = (1/2)\,(B_o)^2\,A_o\,(A_o/A_F).$$

The initial magnetic field and the initial magnetic energy are amplified by a factor of A_o/A_F. Similarly, in a purely inductive electrical circuit, the electrical current and the stored magnetic energy can be increased by reducing the inductance of the circuit. This is illustrated in Fig. 1b,

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where, after an initial current I_O is established in the circuit, the inductance L_O is reduced to zero. Kirchoff's Laws require that magnetic flux is conserved. Therefore,

$$I_F = I_O (L_O+L_L)/L_L$$

where I_F is the final current. The final inductively stored energy is

$$(1/2)\, L_L\, (I_F)^2 = (1/2)\, L_O\, (I_O)^2 \ (L_O+L_L)/L_L$$

Therefore, the electrical current and the stored energy are amplified by a factor $(L_O+L_L)/L_L$. The two examples illustrated in Figure 1, of course, are related since inductance is related to an area crossed by magnetic field lines.

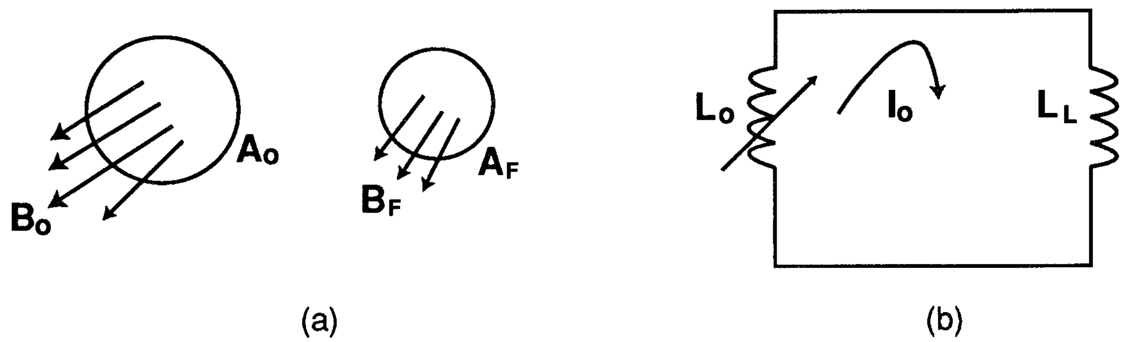

Fig. 1. The magnetic field strength and stored magnetic energy can be increased by: (a) reducing the cross-sectional area of a volume surrounded by a conductor; (b) or, equivalently, reducing the inductance of an electrical circuit.

In magnetic flux compression generators, pressures generated by the release of chemical energy are used to deform electrical conductors, thereby reducing the circuit inductance, performing work on the magnetic field, and transforming chemical energy into magnetic energy. A review of magnetic flux compression generator design considerations is beyond the scope of this paper. Fowler et al., for example, provide an introduction to magnetic flux compression techniques [1]. Suffice it to say here that magnetic flux compression generators (MCG) can produce higher magnetic fields, higher electrical currents, and higher inductively stored electrical energies than any other laboratory technique. Although electrical current and magnetic field strength are related, generators intended to deliver current to external loads generally operate at lower field levels than generators intended to produce high fields for *in situ* experiments.

VNIIEF has created an unmatched magnetic flux compression capability, e.g., electrical currents in excess of 200 MA [2], inductively stored magnetic energies of 200 MJ [3] and magnetic fields exceeding 10 MG in useful volumes [4]. This advanced capability was little recognized in the US until recently, so the US has just begun to ponder possible applications. Through the collaboration, VNIIEF is familiarizing US scientists with its unique capabilities.

The VNIIEF/LANL collaboration merges VNIIEF's advanced magnetic flux compression technology with sophisticated LANL diagnostics and computational techniques. Beginning in September, 1993, six joint experimental campaigns have been conducted to confirm and extend the performance of VNIIEF systems. The campaigns have begun a US evaluation of VNIIEF high-current generator technology for application to imploding liners and to formation of hot, neutron generating plasmas and an evaluation of VNIIEF high magnetic field generator technology for application to high temperature superconductor research and behavior of materials under high pressure. With six campaigns already completed, and additional joint experiments in the planning stages, the collaboration is the most mature of "lab-to-lab" interactions and is serving as a model for broader scientific interactions between the nuclear weapons design institutes of the two nations.

High-Current Experiments

The international pulsed power community has a long-standing interest in ultrahigh electrical current sources. Potential applications of high-current sources include imploding liners for generating ultrahigh pressures, generating soft x-rays, and controlled thermonuclear fusion. VNIIEF's Disk Explosive Magnetic Generator (DEMG) [2] illustrated in Fig. 2 has reached unmatched performance levels in terms of output current and energy. The unique electrical conductor shape of the DEMG provides modularity. Three sizes of DEMG are available, with diameters of 25 cm, 40 cm, and 100 cm. Up to 25 modules have been demonstrated with the 40 cm size. A 3-module, 100-cm-diameter DEMG has produced 100 MJ at 256 MA, so inductively stored energies approaching 1 GJ appear possible.

On September 22, 1993 the first joint experiment involving nuclear weapons design laboratories of the US and Russia was performed at Arzamas-16 when a VNIIEF-designed combination of DEMG and electrically exploded fuse fast opening switch delivered a 20 MA, 0.7 μs pulse to an imploding liner load. An drawing of the experiment is shown in Fig. 2. A helical flux compression generator was used as a "pre-amplifier" to provide the initial magnetization current (nominally 6 MA) for the 15-module, 40-cm-diameter DEMG. The nominal output of the DEMG was expected to be 60 MA and the fuse was expected to deliver as high as 35 MA to the imploding liner load. However, a transmission line insulation failure limited the current to the load to about 20 MA. Nevertheless, LANL optical current measurements confirmed the DEMG performance. Complete experimental results and comparison with LANL computational results are reported separately in these proceedings [5].

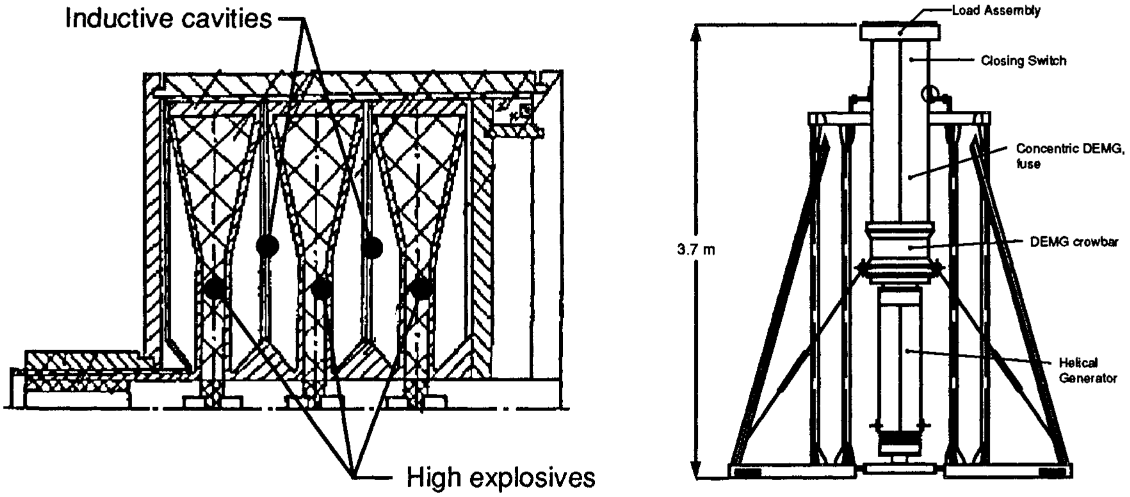

Fig. 2. Left: a 3-module DEMG. Right: the September 22, 1993 experiment as it appeared at the firing point.

The ability of the LANL model of the DEMG and associated circuit elements to predict or reproduce essentially all electrical diagnostic features provides confidence in the use of the model to evaluate performance of DEMG-based systems in a variety of contexts. For example, ultrahigh pressures can potentially be generated with excellent symmetry in a material target by impacting the target with a magnetically accelerated imploding liner. To generate 100 Mbar in uranium or tungsten, impact velocities of 4 cm/μs are required. For cm-scale targets, impactor masses of 350-500 g are required, leading to liner kinetic energies exceeding 250 MJ. Simple electrical circuit analysis requires 350-800 MJ of stored electrical energy at 250-400 MA.

A second example is the generation of soft x-rays. Imploding liners have been pursued for two decades as a means of generating soft x-rays. In the traditional approach, high-voltage is

delivered to an imploding plasma annulus (injected gas puff or thin solid, metallic foil [6]). The high-voltage source is generally either a Marx bank coupled with an pulse-forming line or an inductive store system coupled with a fast opening switch. The high-voltage presents potential vacuum interface problems. Even when the interface problems are solved, magnetically driven instabilities degrade the plasma implosion.

As the only existing pulsed power source capable of delivering 5 MJ and more to an imploding load, the DEMG opens new possibilities for generating soft x-rays. VNIIEF's Changing Mass Liner (CML) x-ray generation concept is a combination of novelty and operational simplicity. In the CML concept, current is delivered to a very massive liner which is accelerated to relatively slow velocity, e.g., 4 mm/μs. When current and inductively stored energy reach maximum, the massive liner reaches the end of one electrode, and a plasma arc, or "bubble," is formed. As the bubble implodes, it thins and its mass per unit length decreases. With proper choice of parameters, there is hope that the imploding plasma reaches a velocity of 30-40 cm/μs which is suitable for soft x-ray production. Although there is no guarantee that the bubble forms as nicely as simple models predict, if the concept is successful, it has the advantage of eliminating the need for a fast opening switch and there is some hope that the changing mass per unit length may lead to more stable implosions.

In February, 1995, a joint experiment was performed at VNIIEF to examine the bubble formation process. The VNIIEF/LANL team was joined by representatives of the Phillips Laboratory (PL). VNIIEF fielded numerous inductive, light, and piezoelectric probes. LANL and PL fielded inductive, light, and voltage probes, and a microwave interferometer. The diagnostics were intended to determine the time of bubble formation and the shape of the bubble as it imploded toward a diagnostic package located at half the initial radius of the massive liner. At the time this article is written, the analysis of the experimental results is in progress. However, it is known that the 5-module, 40-cm-diameter DEMG performed well within its nominal operating range, delivering 65 MA to the load with a peak current derivative of 10^{13} A/s. The measured output current is shown in Fig. 3. Complete experimental results as well as the theory of operation will be reported in another forum [7].

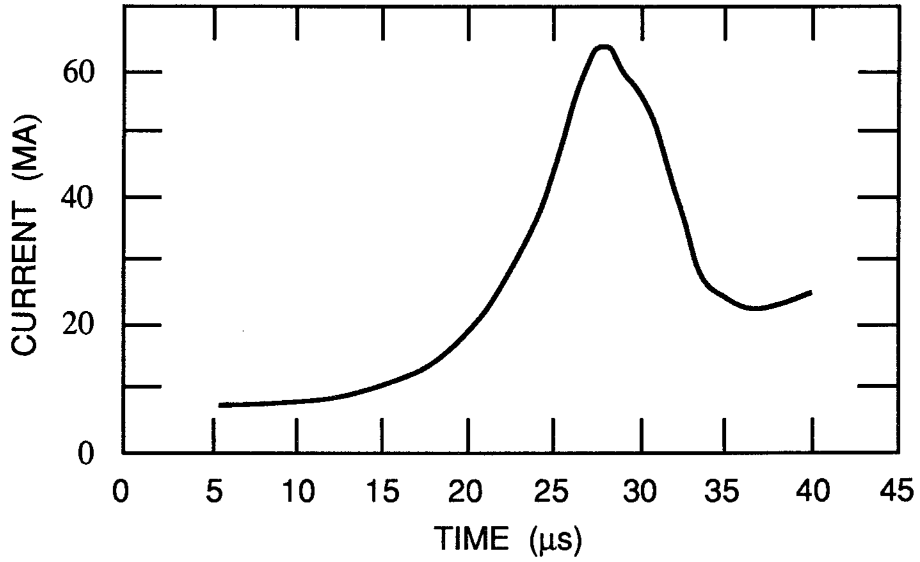

Fig. 3. DEMG current delivered to an imploding liner, plasma "bubble" load.

High Magnetic Field Applications

Ultrahigh magnetic fields offer a wealth of basic research opportunities. Potential applications include high-field and high-temperature superconductivity, the Faraday effect, cyclotron resonance, isentropic compression to high pressures, magneto-optical properties, plasma physics, astrophysics, energy research, and related endeavors.

The VNIIEF MC-1 high-magnetic-field generator, shown in Fig. 4, reproducibly produces magnetic fields higher than 10 MG in cm-scale volumes [4]. The generator uses a set of concentric cylinders, or cascades, to overcome the instabilities which plagued early attempts to generate high fields. Each cascade consists of numerous, small copper wires embedded in an epoxy matrix. Initially, the wires are not in contact, so each cascade is essentially an insulator which allows magnetic flux to pass through. However, when a strong shock wave passes through the cascades, they become conducting and "trap" magnetic flux within them. The high-explosive charge generates the shock which causes the transition in the outer cascade. Subsequent collisions between cascades create the shocks which cause the transition in the inner cascade. Diameters of the cascades are chosen so that another cascade enters the magnetic flux compression process just as instabilities degrade the process.

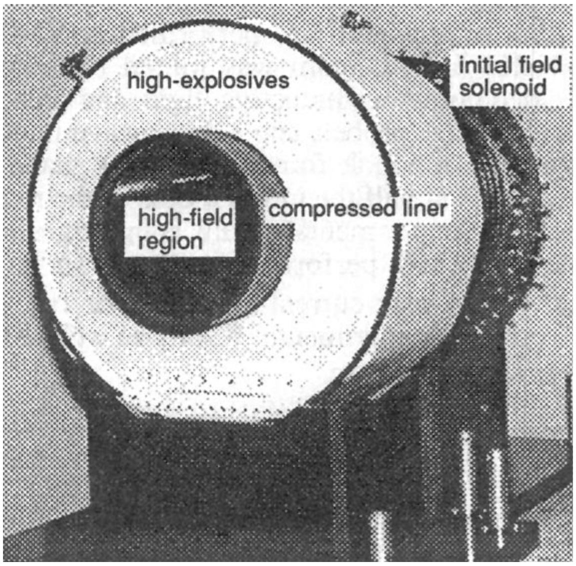

Fig. 4. The VNIIEF MC-1 high-magnetic field generator. The inner cascades are not shown.

In December, 1993, at LANL, VNIIEF MC-1 generators and LANL explosives and diagnostics were used to study the upper critical field of the high temperature superconductor YBCO. Under a sufficiently high magnetic field strength, superconductors lose their superconducting properties and undergo a rapid increase in resistance. The MC-1 is the only generator capable of developing the transition, or "upper critical," field strengths predicted by some theoretical models of the transition process. After a series of developmental tests to confirm the operation of the MC-1 using LANL explosives, the upper critical field of YBCO was measured for the first time. Complete experimental results are reported separately in these proceedings [8].

The performance of the MC-1 using two different US high-explosives was also investigated in December, 1993 at LANL. It was found that performance using "Composition B" was similar to that using VNIIEF explosives, whereas the more-energetic 9501 lead to higher field strengths and faster operation. Complete experimental and computational results are reported separately in these proceedings [9].

The magnetic pressure at 10 MG is 4 Mbar. Theoretical models of the behavior of matter at high pressure predict that beginning in the megabar range, an overlap of electron orbitals results in quasi-molecular or metallic behavior in the noble gases, leading to a softening of the equation of

state, shifts in energy levels, and large changes in transport coefficients. The MC-1 provides a means of investigating material properties at high pressure. The sample to be tested is placed within a conducting cylinder which is placed within the MC-1. Because of the good conductivity of the cylinder, magnetic flux is excluded from the sample volume. As the MC-1 operates, the increasing magnetic field exerts an increasingly high magnetic pressure on the conducting cylinder, which in turn compresses the sample. Because the magnetic pressure rises slowly (compared to explosives), the compression process can potentially be approximately isentropic.

A joint August, 1994 isentropic compression experiment at VNIIEF reached pressures of 6.4 Mbar in argon. Excellent agreement was obtained between predicted compression and compression observed using betatron radiography. At the pressure achieved, quasimolecular behavior should take place. Follow-up experiments will concentrate on measuring electrical conductivity.

Progress Towards Controlled Thermonuclear Fusion

For more than four decades, controlled thermonuclear fusion has been one of the most exciting, and most frustrating, applications of pulsed power technology. Fusion research has evolved into two mainline approaches, Magnetic Fusion Energy (MFE) and Inertial Confinement Fusion (ICF), and pulsed power has played a major role in the progress made by both approaches.

At VNIIEF, controlled fusion is often referred to as "Sakarov's fondest dream." Building on ideas originally proposed by Sakarov, VNIIEF has made major advances in a novel approach to controlled fusion known in Russia as MAGO (MAGnitnoye Obzhatiye, or "magnetic compression") and in the US as MTF (Magnetized Target Fusion). MAGO/MTF is a relatively untried approach to fusion ignition which uses a magnetic field within a fusion target to suppress thermal conduction energy losses while retaining the implosion heating and inertial confinement advantages of conventional ICF. In plasma density and time scale, MAGO/MTF is intermediate between the ten orders of magnitude which separate ICF and MFE. The reduced losses in MAGO/MTF potentially permit adiabatic compression of the fusion fuel to ignition even at low (e.g., 1 cm/μs) implosion velocity. And, because the implosion process begins with the plasma at an elevated temperature, the convergence ratio of the pusher can potentially be less than 10, depending upon the initial temperature and the adiabaticity of the implosion process.

A MAGO/MTF system requires two elements: (a) a target implosion driver; (b) a means of preheating and magnetizing the thermonuclear fuel within the target prior to (or during) the implosion.

US work in the mid-1970's and early 1980's demonstrated some of the basic principles of MAGO/MTF. Experiments at Columbia University demonstrated classical reduction of thermal conduction in a wall-confined, magnetized plasma [10]. Experiments at Los Alamos demonstrated good symmetry in a liner driven magnetically to a velocity of 1 cm/μs and a radial convergence of 10 [11]. The 3-mm-diameter "phi" target experiments at Sandia National Laboratory produced 10^6 neutrons at an implosion velocity of 4 cm/μs [12] and provide a "soft proof of principle" of MAGO/MTF; two-dimensional magnetohydrodynamic computations predicted that essentially no neutrons would have been produced at such low implosion velocity without the preheating and magnetization of the fuel [13]. More recently, the Phillips Laboratory has demonstrated a quasi-spherical magnetically driven shell implosion, conceptually appropriate for a MAGO/MTF target pusher [14].

VNIIEF has made major advances in both elements required in a MAGO/MTF system. DEMG-powered experiments have delivered 25 MJ of kinetic energy to an imploding liner [15]. Such energy appears to be more than adequate to achieve fusion ignition via MTF. However, additional work is required to determine the optimal implosion velocity and optimal imploding liner, or pusher, shape for an ignition demonstration experiment.

VNIIEF has also made major progress in forming a plasma suitable for subsequent implosion [16]. Three joint experiments--one at VNIIEF in April, 1994, and two at Los Alamos in October, 1994--have been aimed at characterizing the plasma produced in VNIIEF's unique chamber. The chamber is powered by a helical flux compression generator and explosively operated opening and closing switches. The plasma formation system is shown in Fig. 5. The most recent experimental results, and corresponding two-dimensional computations, are reported separately in these proceedings [17,18]. The computations are in reasonable agreement with the experimental observations. For time later than about 4 μs, i.e., after the very complex early-time plasma formation process, the computations show a plasma having parameters suitable for subsequent implosion; average computed late-time plasma parameters are n_e=1.6 x 10^{18}/cm^3, ρ=6.7 x 10^{-6} g/cm^3, T=130 eV, B=240 kG, β=0.3, $(\omega\tau)_e$=140.

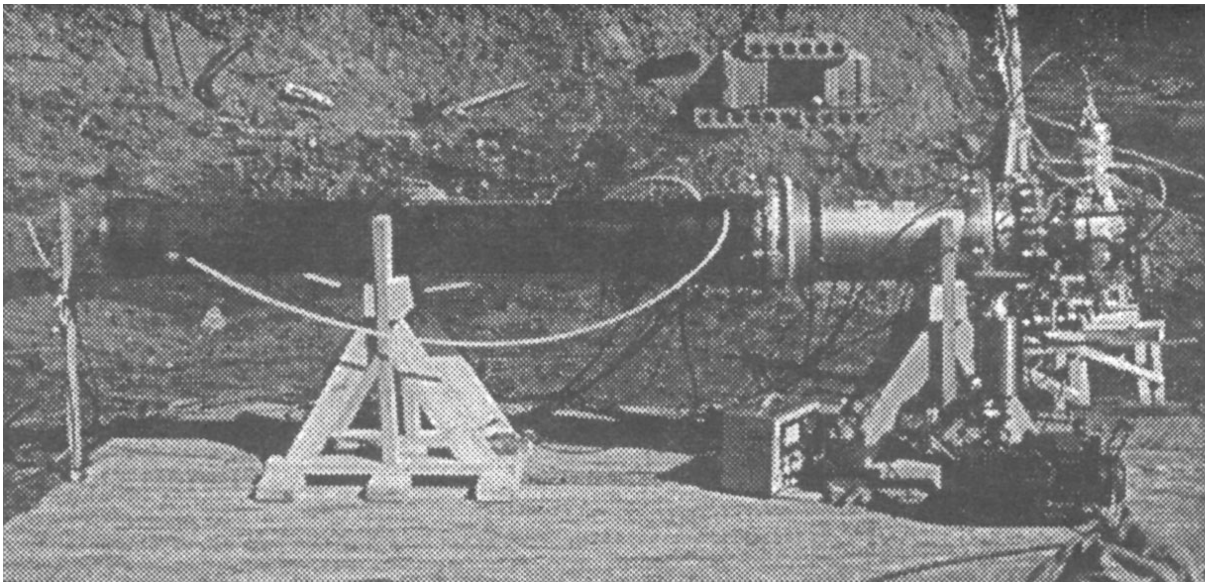

Fig. 5. The VNIIEF MAGO plasma formation system. The dark cylinder on the left is a helical flux compressor. To the right of the generator are an explosively operated closing and opening switch, and the heavily diagnosed plasma chamber is at the far right.

Results of survey spherical target computations [19] based upon the experimental plasma mass (8.9 mg), average computed temperature and magnetic field, and an implosion kinetic energy of 65 MJ are summarized in Fig. 6. A region of unity gain (curve b) occurs for initial densities above about 10^{-6} g/cm^3 and initial velocities above approximately 0.2 cm/μs. Gains in excess of ten (curve a) occur for densities and velocities approximately 2-3 times higher. A gain of 16, and a thermonuclear yield of 1 GJ, is predicted for a density of 6.7 x 10^{-6} g/cm^3 (the computationally predicted density achieved experimentally), a pusher implosion velocity of 2 cm/μs and a maximum radial convergence of less than 20. The survey computations show that the 290 eV average temperature computed for an earlier, lesser diagnosed experiment [18] can significantly reduce the convergence required and that approximately adiabatic compression can be expected for initial magnetic fields as low as 75 kG.

The survey results (Fig. 6) coupled with the two-dimensional computations suggest that a plasma suitable for subsequent implosion in a MAGO/MTF context has been produced in the joint plasma formation experiments. Further plasma formation experiments are required before the plasma chamber can be confidently mated with an implosion system. Future experiments will emphasize characterization of the late time plasma behavior and will search for wall and insulator

impurities which would degrade the implosion heating process by enhancing the radiation energy losses from the plasma. Although it is quite plausible that the present plasma chamber could be scaled to a smaller size, reducing the implosion energy required, existing DEMGs are sufficient to provide the 65 MJ of energy used in the survey computations of Fig. 6. Thus, an attractive feature of MAGO/MTF is that the best available theoretical models suggest that fusion ignition is possible without a major capital investment in driver technology.

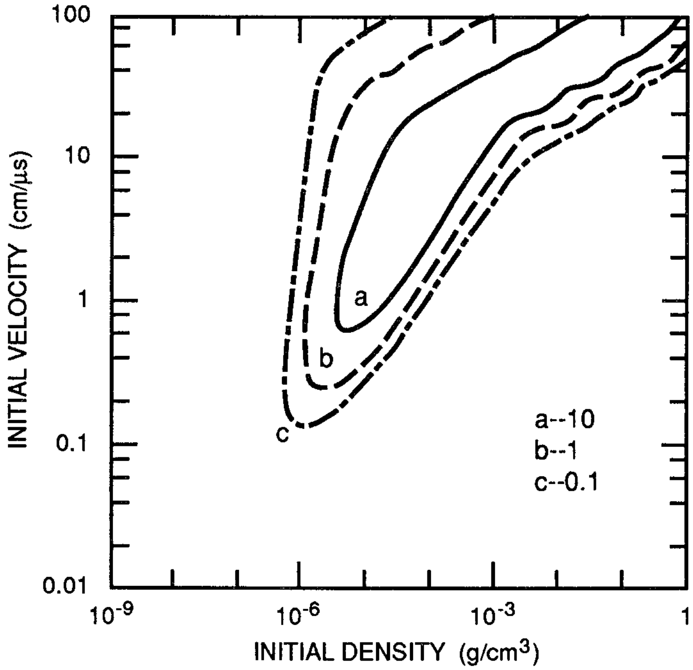

Fig. 6. Gain contours computed using model of [19]. Mass: 8.9 mg. Initial kinetic energy: 65 MJ. Minimum initial temperature: 130 eV. Initial magnetic field: 240 kG.

Concluding Remarks

VNIIEF and LANL have now collaborated in six major experimental campaigns. Each campaign has been based on unique VNIIEF magnetic flux compression technology. The collaboration has brought demonstrable scientific benefit to the Russian Federation and to the United States.

If the political relationship between the two nations remains positive and adequate funding is obtained, the VNIIEF/LANL collaboration will be long-term partnership. A second isentropic compression experiment will be performed at VNIIEF in August, 1995. Another MAGO/MTF plasma formation experiment is scheduled for September, 1995 at VNIIEF; LANL will field extensive x-ray diagnostics in an effort to determine the late-time temperature of the plasma. Mutual interest has been expressed in jointly designing and developing a high-magnetic field generator capable of producing 20 MG in a useful volume. A decision whether or not to pursue the CML soft-x-ray concept will be made after the initial experimental results are analyzed. A 100-MJ-class DEMG experiment delivering more than 20 MJ of kinetic energy to a liner is under consideration as a step toward 100 Mbar shock pressures and toward a MAGO/MTF implosion system. If future plasma formation experiments confirm that a plasma suitable for subsequent implosion is available, funding will be sought to pursue a path culminating in a fusion ignition demonstration.

The remaining authors regret the loss of their colleague, Academician Alexander I. Pavlovskii, who died unexpectedly in February, 1993, too soon to see the collaboration for which he worked so hard come to fruition.

Because VNIIEF and LANL developed the first nuclear weapons of their respective nations, it is perhaps symbolic of a future of reduced global tensions that VNIIEF and LANL have started their second half-century working side-by-side. The participants in the collaboration are continually cognizant of the comment made by former LANL Director Norris Bradbury: "the whole object of making nuclear weapons is not to kill people, but to find time for somebody to find other ways to solve these problems."

This collaboration would not have been possible without the support and encouragement of many officials of the governments of Russia and the United States and many administrators and colleagues at the All-Russian Scientific Research Institute of Experimental Physics and the Los Alamos National Laboratory.

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